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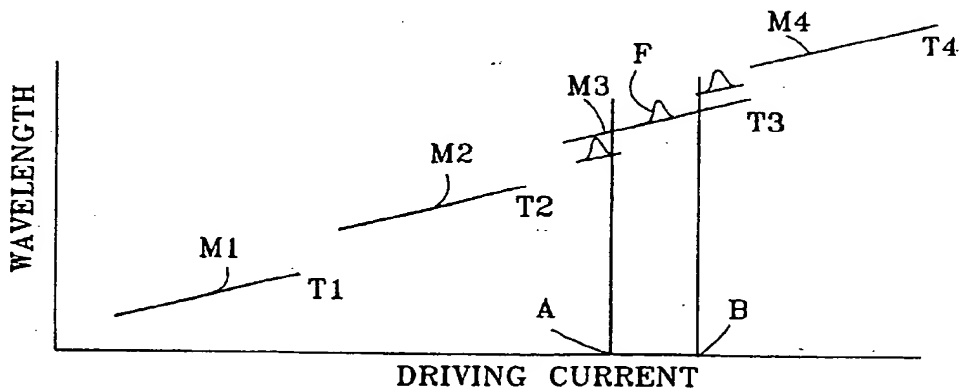

(57) Abstract

A method is described of controlling the frequency of a laser diode so that it locks onto a desired frequency of an etalon and always operates in the same lasing mode. The method is achieved by selecting an etalon having the appropriate passband of frequencies, selecting an operating temperature (T3) for the laser which is at a level corresponding to the required lasing mode (M3) of the laser diode, selecting an initial temperature from which the operating temperature of the laser diode can only be approached in one direction, selecting a range (A to B) for the level of the driving current of the laser diode which includes the driving current level which produces the desired frequency of operation of the laser diode at the operating temperature, and selecting an initial driving current which is at a level from which the desired frequency can only be approached by varying the driving current in one direction, changing the temperature of the laser diode from its initial temperature to the operating temperature (T3) and with the temperature of the laser controlled at its operating temperature, changing the driving current from its initial level under the control of a feedback system including the etalon until the frequency of the laser diode reaches the desired frequency corresponding to point F of the etalon characteristic.

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FREQUENCY STABILISATION OF A LASER DIODE

The present invention relates to semi-conductor laser diodes and in particular to a means of achieving stability in the frequency of the output of the lasers.

It is known to use an etalon as an element of a control system which detects changes in the frequency of the output of the laser diode, and to use a signal derived from such changes in a feedback loop to control the temperature, or drive current of the laser diode. An example of such a system is described in U.S. Patent No. 4,583,228.

The present invention provides an improved control system for controlling the frequency of a laser diode with greater accuracy than has hitherto been achieved. A particular feature of the invention is that it provides the ability to ensure that the laser diode operates not just at a fixed frequency, but at the same fixed frequency every time it is operated.

This is achieved in accordance with one aspect of the invention by the following steps:

a) select an appropriate etalon. This will preferably have widely spaced passbands of frequencies to assist in the process of locking on to a particular one of its passbands,

b) select an operating temperature for the laser diode which is at a level corresponding to a required lasing mode of the laser,

c) select an initial temperature which may be above or below the operating temperature of the laser, so that to get from the initial temperature to the operating temperature, the temperature of the laser diode always has to be changed in the same sense (i.e. either up or down),

d) select a range for the driving current of the laser diode which extends from a minimum value, at which the laser would operate at a frequency above the passband frequencies of the etalon in the required lasing mode, but lower than the passband frequencies of the etalon for the next higher frequency lasing mode, to a maximum value, at which the laser would operate at a frequency below the passband frequencies of the etalon in the required lasing mode, but above the passband frequencies of the etalon at the next lower frequency lasing mode,

e) increase (or decrease) the temperature of the laser to its operating temperature. This may take place with the laser off, or switched on using the minimum or maximum value of the drive current,

f) switch in a temperature control circuit to hold the laser at its operating temperature,

g) increase (or decrease) the driving current to the laser slowly, in continuous manner or in small steps, until the frequency of the laser reaches the passband of the etalon at the required lasing mode,

h) lock in a current control feedback loop based on a frequency within the passband of the etalon to maintain the frequency at a desired part of the passband of the etalon.

The laser diode is preferably mounted on a base, the temperature of which is controlled, and other ones of the critical electronic components of the control system may be mounted in thermal contact with the same temperature controlled base.

The passband frequencies of the etalon and their spacing are established by its design. The selection of the

passband to be used for locking the frequency of the laser diode can be made in different ways.

It is known, for example from U.S. Patent No. 5,331,651 that the passband frequency of an etalon can be varied by mounting the etalon at an angle to the laser beam and varying the angle.

This method may be used in the apparatus of the present invention, first to select the required passband of frequencies of the etalon, and then to fine tune the passband by moving it slightly during the set-up process. To achieve this the etalon is mounted on a rotatable platform, and rotated until the desired passband of frequencies appropriate to the required frequency of the laser diode has been located.

In another novel aspect of the present invention, the etalon is mounted at a fixed angle on a temperature controlled base and the passband of frequencies required is found by varying the temperature of the etalon. Thereafter the apparatus is operated with the temperature of the etalon controlled at the same level to maintain the correct passband.

The temperature controlled base may be the same as that on which the laser diode is mounted, or it may be a separate independently controlled base. In the latter case it becomes feasible, instead of operating the etalon at a fixed temperature, and hence a fixed passband of frequencies, to control the etalon temperature based on variations in the refractive index of the atmosphere in which the apparatus is working. In this way the laser diode frequency may be locked on to a frequency of the etalon which is varying with refractive index changes so that the laser diode operates at a constant wavelength. The invention will now be more particularly described, with reference to the accompanying drawings, in which:

Fig 1 is an illustration of the relationship between the intensity of light passing through the chosen etalon and the frequency of the light from the laser diode;

Fig 2 is a plot illustrating the relationship between the lasing modes of the laser diode and its drive current at different temperatures;

Fig 3 is a flow diagram showing the main components of the electronic control system of the present invention;

Fig 4 is a view of the main mechanical and electrical components of the system mounted within a housing of the laser;

Fig 5 is a flow diagram showing the main components of an alternative embodiment of the present invention.

Referring now to the drawings, Fig 1 shows the characteristic plot of transmission intensity against frequency which is required of an etalon for use in the control system of the present invention. It can be seen that the etalon has relatively narrow discrete passbands spaced at intervals along the frequency axis. To ease the problem of locking onto any one of the passbands, it is preferable to select an etalon which, by its construction, has widely spaced passbands of frequencies.

Fig 2 shows the wavelengths (left hand vertical axis) of the various lasing modes of a laser diode plotted against its driving current at different temperatures T1 to T4.

The solid lines show that as temperature increases the wavelength increases gradually within a lasing mode, until at certain points the laser hops to another mode at a greater wavelength. Fig 2 also illustrates by means of the shorter dotted lines that as the driving current changes, the laser will also hop into different modes.

It is to be understood that although, for convenience, Fig 2 shows wavelength variation, because of the relationship between the frequency and wavelength of the laser, the frequency of the laser is also changed in the different modes.

In the past, control systems have controlled both the drive current and the temperature to obtain a fixed frequency within a lasing mode, by locking the frequency to a frequency within a passband of frequencies of an etalon.

However, it can be seen that depending on the temperature and drive current of the laser diode, and the characteristic of the etalon, although the frequency may be held stable for any given operation, there is no guarantee that in any subsequent operation, the laser will be locked at the same frequency.

The control system of the present invention will enable the same lasing mode to be selected at the same frequency every time the laser is switched on.

Referring now to Fig 3, the components of the control system include a laser diode 10, which produces a beam 12 of coherent light which is collimated by a lens 14 and directed towards a beam splitter 16. At the beam splitter 16, a portion 18 of the laser beam is transmitted and a portion 20 is reflected.

The reflected portion 20 is directed towards an etalon 22 which may be solid or hollow, and which is mounted so that it lies at an angle to the beam 20. One benefit of mounting the etalon at an angle to the beam is that light reflected from its front and rear reflecting surfaces is not directed back into the laser diode 10.

The etalon transmits light to a photodiode detector 24 only at a certain passband of frequencies (as shown in Fig 1)

depending on the frequency of the laser beam 12. The photodiode detector 24 therefore provides an output signal having a characteristic similar to Fig 1. The output signal is passed via a current/voltage converter 25 to a differential amplifier 26 in the control circuit.

The transmitted beam 18 is directed to a second beam splitter 27, at which a portion 28 of the beam 18 is reflected to a second photodiode detector 29, and a further portion 30 is transmitted for further use. The output signal of the photodiode detector 29 is also passed via a current/voltage converter 31 to the differential amplifier 26. By comparing the outputs of the two photodetectors 24 and 29 in the differential amplifier 26, fluctuations in the intensity of the laser beam 12 can be eliminated from the output of the differential amplifier 26, which will once again have a characteristic similar to Fig 1. The output of the differential amplifier 26 is passed as an error signal to a current controller 40 which modifies the supply of current to the laser diode.

The etalon is preferably chosen to have only a single pass band of frequencies over the frequency range of any one stable lasing mode of the laser diode. This is illustrated in Fig 2 by the small peaks superimposed on the short dotted lines of the Figure. However, if this is not possible the most suitable passband can be selected to control the laser.

When the apparatus is being set up, the angle of the etalon with respect to the beam 20 is fine-tuned to ensure that the correct passband of frequencies for the selected lasing mode is obtained. This may be done manually, or by mounting the etalon on a rotatable base indicated by reference numeral 21 in Fig 3, and providing a feedback 23 from the differential amplifier 26 to indicate the changes in frequency as the etalon is rotated. Once the correct

passband has been located the angle of the etalon is locked.

An initial temperature is selected for the laser diode which is such that in order to reach the operating temperature, the temperature of the laser diode will always be changed in the same sense. Thus, for example, we have found it convenient to select an operating temperature well above ambient temperature, so that ambient temperature can be regarded as the initial temperature and the laser diode will always be heated to reach its operating temperature. Alternatively the operating temperature may be selected to be well below ambient temperature so that, once again, ambient temperature may be regarded as the initial temperature and the laser diode will always be cooled to reach its operating temperature.

Clearly other possibilities can be chosen. For example, the laser diode may be heated to an initial temperature higher than its operating temperature and allowed to cool down to reach its operating temperature, or it may be cooled to an initial temperature lower than its operating temperature and allowed to warm up to its operating temperature.

In order to ensure that the initial temperature can be reached whether the ambient temperature is high or low, a Peltier element may be used which can act as a heater or a cooler.

In the present example the operating temperature is set at 30°C, and for most areas of use of the laser diode it is sufficient to supply a heater to raise the temperature of the laser diode from ambient temperature to the operating temperature. Thus the control system, shown in Fig 3, also includes a heater 32, a temperature sensor 34, and a temperature control 36 connected to the temperature sensor which provides a feedback control to the heater current to

maintain the temperature of the laser diode constant at its operating temperature.

The operating temperature is also selected so that the laser diode operates in a stable lasing mode at the operating temperature.

The driving current of the laser diode is given a nominal setting by a first control circuit 37 and a limiting device 38 (Fig 3) to be within the range A to B (Fig 2) which is wide enough to cover the complete range of frequencies of the laser diode within the lasing mode at the selected operating temperature, but where A is above the passband frequencies of the etalon at the next lower frequency lasing mode on the driving current characteristic, and B is below the passband frequencies of the etalon at the next higher frequency lasing mode on the driving current characteristic.

The operation of the temperature controller 36, and the current controller 40 are controlled by a logic device 41 via switches 42 and 43.

One method of achieving the required lasing mode on switch on is as follows:

The laser is switched on using the minimum driving current level A. This establishes the operation of the laser diode within the proper range of lasing modes which include that of the selected operating temperature.

The heater 32 is switched on by the logic controller 41 and the temperature of the laser diode thus increases from the ambient temperature, which is regarded as the initial temperature, thus ensuring that the selected operating temperature and hence the required lasing mode are approached from the same direction each time the laser is switched on. In the present example the laser will switch

through its lasing modes upwardly through M_1, M_2 etc until at the operating temperature it settles down in mode M_3.

When the operating temperature is reached, the logic controller switches in the temperature controller which holds the laser at this temperature. Simultaneously logic controller switches in the current controller 40 which increases the driving current from the minimum level A through the range A-B. This gradually decreases the frequency of the laser within the mode M_3 until a signal is obtained from differential amplifier 26 that the passband frequencies of the etalon have been reached. The driving current is further increased to bring the frequency to a point F on the etalon characteristic, which is below the maximum frequency, so that small current changes will provide significant intensity changes and control of the frequency within a very narrow range of the mode M_3 is facilitated.

Thus it can be seen that at the required operating temperature, only a single mode M_3 will be used, and within that mode the frequency of the laser can be held to a very narrow range of variation, by using the output of the differential amplifier 26 as a feedback signal to the current controller 40, to hold the driving current constant at the required value.

Clearly, if the operating temperature is set at a lower value than ambient temperature and a cooler is used, the control system will operate to lower the temperature of the laser so that its frequency drops downwards through the lasing modes to a specified mode, and the driving current may be held at the maximum value until the operating temperature is reached. Thereafter the driving current will be lowered until the passband frequencies of the etalon is reached.

Fig 4 shows the mounting arrangement of the various components of the system. The laser diode is mounted on a conducting metal base 50 which is large enough to accommodate the temperature sensor 34, the heater 32, the etalon 22, and the two photodiode detectors 24 and 30. By this means all of these components are maintained by the temperature control circuit at a constant temperature which is the same as, or close to, that of the laser diode. This eliminates inaccuracies in the system which might otherwise occur due to temperature variations of the components.

Other electronic components of the control system shown inside the dashed line of Fig 3 are mounted on a board 26 and this, or part of it, is also arranged to be in intimate thermal contact with the heated base so that other key electronic components which are temperature sensitive, for example the current/voltage converters and the electronics of the temperature sensor are also maintained at a constant temperature.

The above system has been described with reference to the use of an etalon to which the frequency of the laser diode is linked. This is beneficial for many applications of laser.

Where laser diodes are used in measurement systems for example laser interferometers, it is more important that the wavelength of the laser beam through the measurement medium is maintained constant. This can be achieved in accordance with the present invention by using a hollow etalon which can act as a tracking air refractometer and varying the drive current of the laser diode in accordance with signals from the refractometer so that the frequency of the laser varies over a small range as the refractive index of the air varies.

Alternatively an absolute air refractometer may be introduced into the control system and a characteristic of

the etalon, (e.g. its temperature or angle) varied in accordance with variations in the refractive of the atmosphere through which the laser beam passes.

A suitable refractometer for this purpose is described in our published European patent specification no. 508583A1.

A further embodiment of the invention will now be described with reference to Fig 5.

Many parts of the apparatus required for this embodiment are the same as those which have been described in relation to the previous embodiment, and the same reference numerals have been used to identify these parts.

In this embodiment, the etalon 22 is mounted at a fixed angle and the correct passband of frequencies required for the particular laser is selected by fine tuning the etalon using a temperature control device 60. The etalon is mounted on a base 62 which may be heated (or cooled), for example, by a peltier device 64. A connection 66 is made to the output of the differential amplifier 26 to provide a feedback loop to control the temperature of the device 60 in accordance with any changes in frequency of the beam 20. These are detected by changes in the intensity of the light detected by the photodiode 24.

The temperature controlled base 62 is controlled independently of the base 50 for the laser diode, and the other electronic components. This has two advantages. First it allows greater freedom of choice in the materials from which the etalon is made. For example, materials having high coefficients of thermal expansion require a more sensitive temperature control to maintain the frequency range, than materials having low coefficients of thermal expansion.

Secondly, the independent temperature control enables additional signals 68 to be fed to it from an air refractometer 70, which allows the passband of frequencies of the etalon to be moved in accordance with the variation of the refractive index of air. Thus the frequency of the laser diode can be locked onto a variable frequency of the etalon in order that the wavelength of the light from the laser diode remains constant.

As an alternative to an air refractometer a device which measures ambient temperature, pressure and humidity and calculates the refractive index of the atmosphere may be used to produce signals 68.

The etalon could be mounted on the base 50 and its temperature controlled to be the same as that of the laser diode. But the materials of which the etalon is made would have to be carefully chosen to ensure that the passband frequency of the etalon was correct at the operating temperature of the laser diode.

In a further alternative the passband frequencies of the etalon can be varied to correct for the temperature of a part being measured. For example, measurements are taken at, or corrected to, a standard temperature of 20°C. Thus if a part being measured is at a different temperature the frequency of the etalon to which the laser is locked can be changed so that the laser measurement is automatically corrected back to the 20°C standard.

If the change in frequency required in the etalon for any reason is greater than can be dealt with by changing the driving current of the laser alone, it may be necessary to vary the operating temperature of the laser to get the laser frequency to match the new etalon frequency while keeping the laser in the same lasing mode. To achieve this the mean value of the driving current (which may be changing rapidly) is kept constant while the laser

temperature is changed.

CLAIMS

1. A method of operating a semi-conductor laser diode in which the frequency of the laser is locked to a desired frequency within a given passband of an etalon, the method comprising the steps of:

selecting an etalon which has the required passband frequency,

selecting an operating temperature for the laser which corresponds to a required lasing mode of the laser in which the laser operates at the desired frequency,

establishing an initial temperature for the laser such that the operating temperature can only be reached by changing the temperature of the laser in the same sense from the initial temperature each time the laser needs to be stabilised,

changing the temperature of the laser from the initial temperature to the operating temperature,

selecting a range for the level of the driving current of the laser which includes the level of current at which the laser operates at the desired frequency at the operating temperature of the laser,

establishing an initial level of the driving current for the laser such that the desired frequency can only be reached by further changing the level of the driving current in the same direction from the initial level each time the laser is switched on,

with the temperature of the laser controlled to keep the laser operating in the same lasing mode, changing the level of the driving current form the initial value until the required frequency of the laser is reached and thereafter controlling the driving current of the laser to maintain the frequency of the laser at the desired frequency of the etalon.

2. A method as claimed in claim 1 and wherein the selecting operating temperature is higher than the initial temperature whereby the temperature of the laser always has

to be increased from the initial temperature to reach the operating temperature.

3. A method as claimed in claim 1 and wherein the selected operating temperature is lower than the initial temperature whereby the temperature of the laser always has to be reduced from the initial temperature to reach the operating temperature.

4. A method as claimed in claim 2 and wherein the initial temperature is the ambient temperature.

5. A method as claimed in claim 1 and wherein the range selected for the level of the driving currently extends from a minimum value, at which the laser would operate at a frequency above the passband frequencies of the etalon in the required lasing mode but below the passband frequencies of the etalon for the next higher frequency lasing mode, to a maximum value, at which the laser would operate at a frequency below the passband frequencies of the etalon in the required lasing mode but above the passband frequencies of the etalon at the next lower frequency lasing mode.

6. A method as claimed in claim 5 and wherein the initial level of the driving current is selected to be the minimum value so that each time the laser is switched on, the driving current has to be further increased from the initial level to reach the desired frequency at the operating temperature.

7. A method as claimed in claim 5 and wherein the initial level o f the driving current is selected to be the maximum value so that each time the laser is switched on the driving current has to be decreased from the initial level to reach the desired frequency at the operating temperature.

8. A method as claimed in claim 1 and wherein the desired frequency of the etalon to which the frequency of the laser is to be locked is made to be varied in accordance with changes in the refractive index of the atmosphere in which the laser is operating whereby the wavelength of the laser diode controlled.

9. A method as claimed in claim 1 comprising the further step of varying the passband frequencies of the etalon.

10. A method as claimed in claim 9 and wherein the step of varying the passband frequencies of the etalon comprises the step of varying the angle of the etalon relative to the laser beam.

11. A method as claimed in claim 9 and wherein the step of varying the passband frequencies of the etalon comprises the further step of varying the temperature of the etalon.

12. A method as claimed in any one of claims 9 to 11 and wherein the passband frequencies of the etalon are varied in dependence upon a parameter external to the system.

13. Apparatus for carrying out the method of claim 9 comprising:

means for varying the temperature of the laser diode,

means for varying the driving current of the laser diode,

control means for controlling the operation of the temperature varying means and the drive current varying means to ensure that the frequency of the laser diode remains locked on the desired frequency of the etalon, and wherein further means are provided for varying the angle of the etalon relative to the beam from the laser diode to vary the passband frequencies of the etalon.

14. Apparatus for carrying out the method of claim 9 comprising:

means for varying the temperature of the laser diode,

means for varying the driving current of the laser diode,

control means for controlling the operation of the temperature varying means and the drive current varying means to ensure that the frequency of the laser diode remains locked on the desired frequency of the etalon, and wherein further means are provided for varying the temperature of the etalon to vary the passband frequencies of the etalon.

15. Apparatus according to claim 14 and wherein the further means include control means for varying the temperature of the etalon in correspondence with variations in the refractive index of the atmosphere through which the laser beam passes.

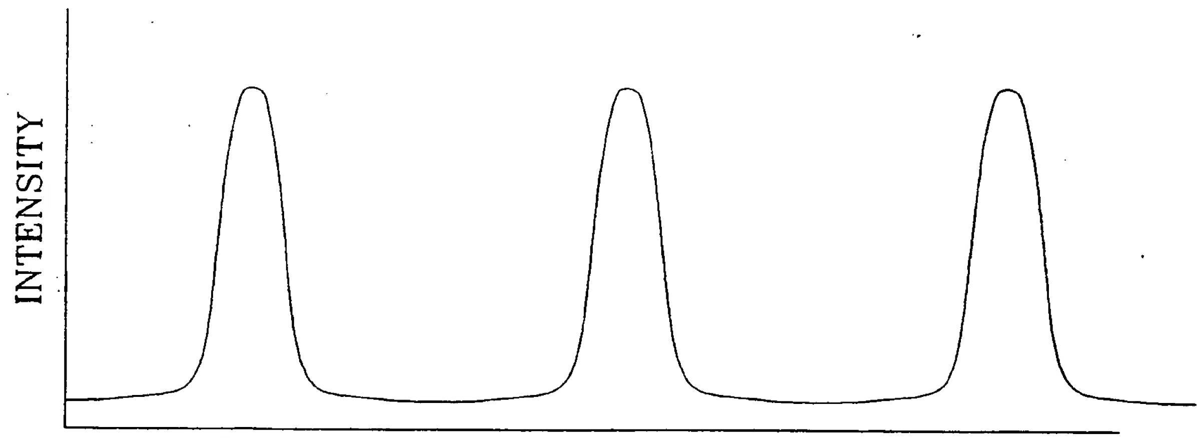

Fig1

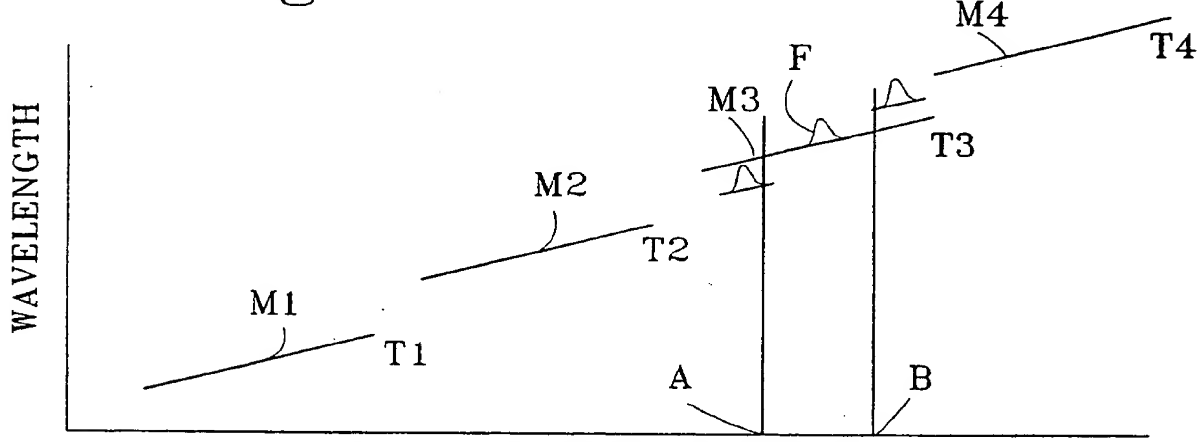

Fig2

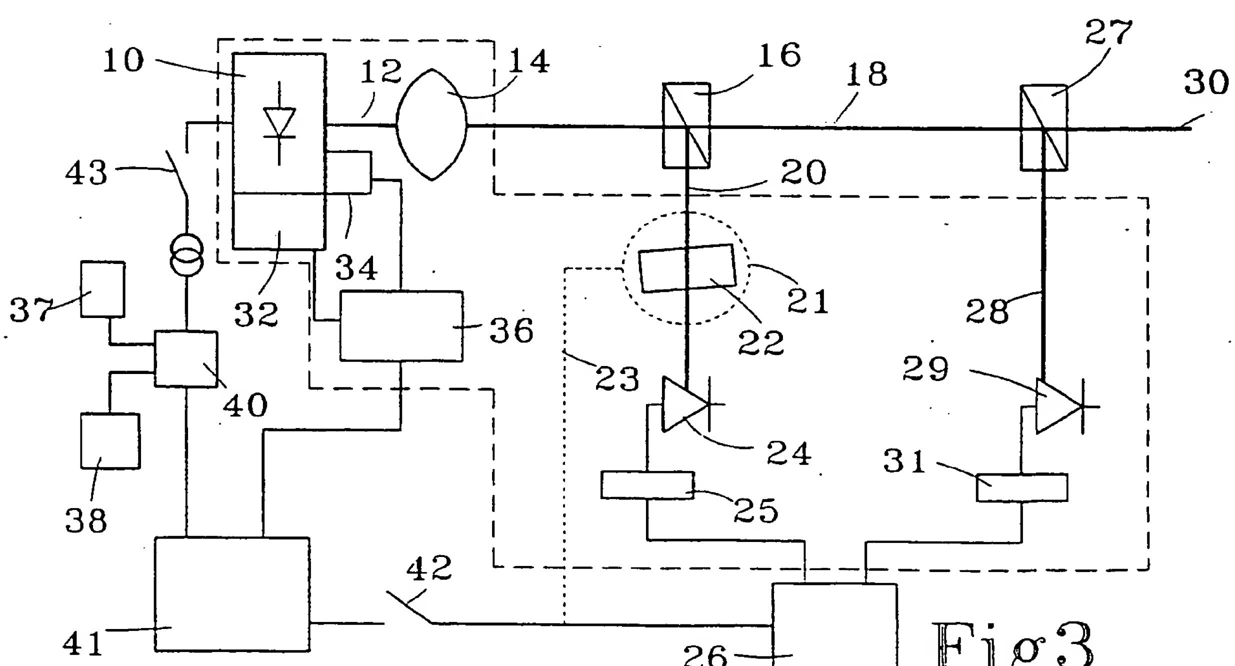

Fig3

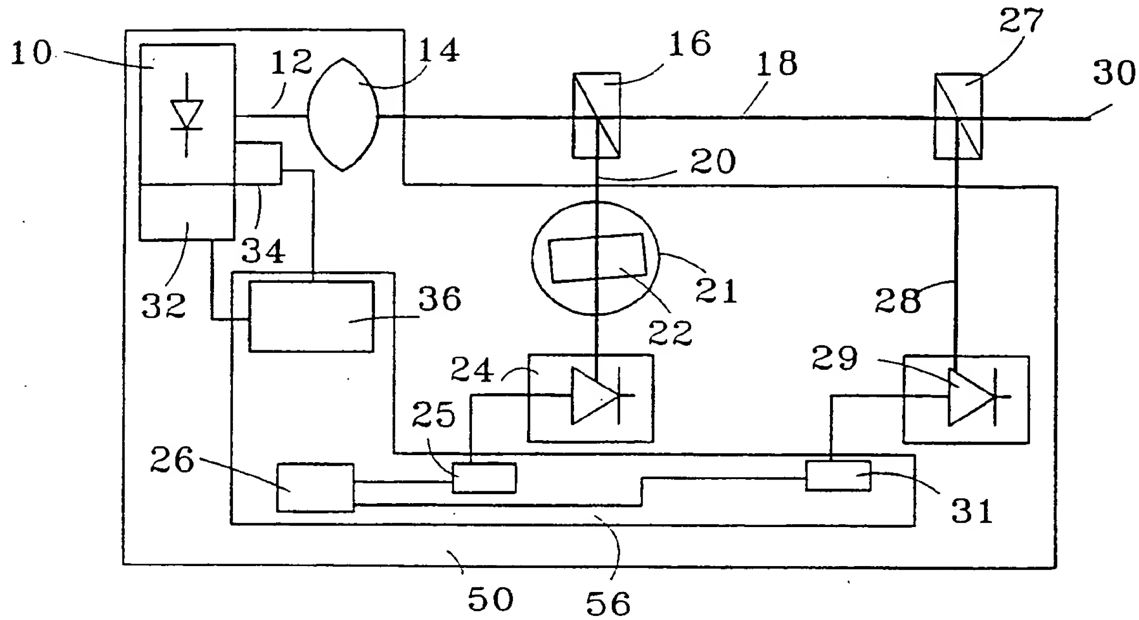
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Fig4

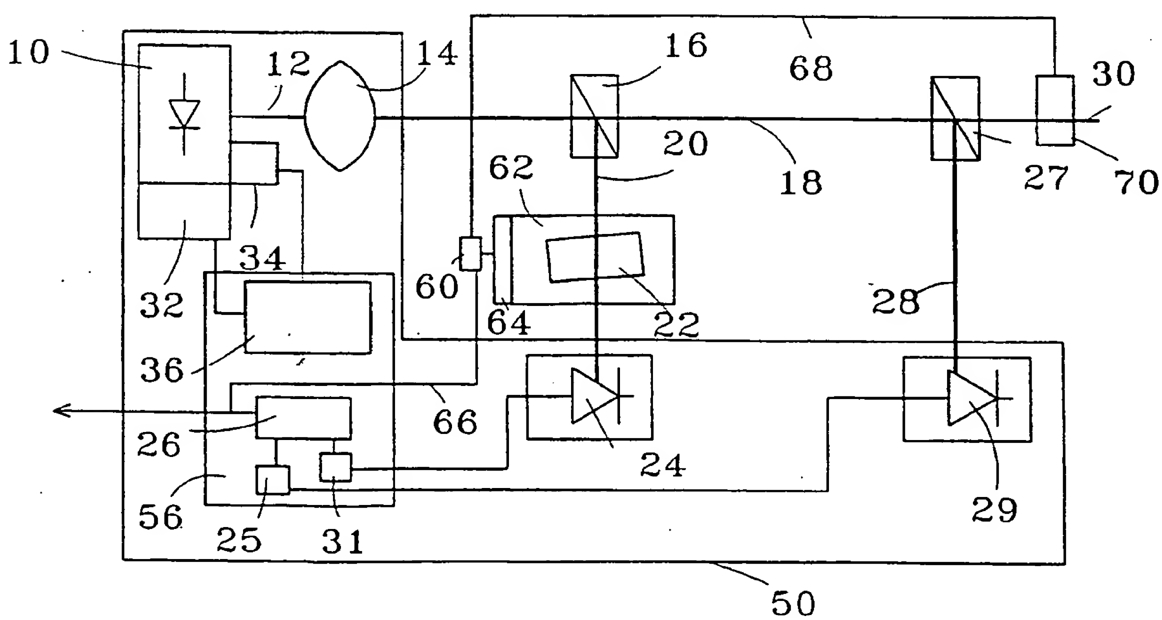
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Fig5

INTERNATIONAL SEARCH REPORT

Inter ›nal Application No
PCT/GB 95/00926

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01S3/133 G01J9/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	DE,A,40 39 371 (ZEISS CARL FA) 11 June 1992	1-7
Y	see page 1, line 60 - page 2, line 22	9-11,13, 14
A	see page 4, line 47 - page 5, line 31; figure 1A ---	8,12,15
A	US,A,4 922 480 (BOSCH FRIDOLIN L) 1 May 1990 see column 2, line 38 - line 50 see column 3, line 23 - column 4, line 18 ---	1-4
A	DE,A,37 06 635 (SPINDLER & HOYER KG) 15 September 1988 see column 6, line 67 - column 8, line 37; figures 1-8 --- -/--	1-4

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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9 August 1995	06.09.95

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European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+ 31-70) 340-2040, Tx. 31 651 epo nl, Fax (+ 31-70) 340-3016	Stang, I

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 95/00926

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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